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Assessment of nitrogen fertilization for the CO_2 balance during the production of poplar and rye

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ABSTRACT

This study was designed to consider all nitrogen fertilizer-related effects on crop production and emission of greenhouse gases on loamy sandy soils in Germany over a period of nine years (1999–2007). In order to set up a CO_2 balance for the production of energy crops, different nitrogen pathways were investigated, such as direct N_2O emissions from the soil and indirect emissions related to NO_3 leaching and fertilizer production. Fluxes of N_2O were measured in an experimental field using closed chambers. Poplar (*Populus maximowiczii* × *P. nigra*) and rye (*Secale cereale* L.) as one perennial and one annual crop were fertilized at rates of 0 kg N ha^{-1} yr^{-1}, 75 kg N ha^{-1} yr^{-1} and 150 kg N ha^{-1} yr^{-1}. The mean N_2O emissions from the soil ranged between 0.5 kg N ha^{-1} yr^{-1} and 2.5 kg N ha^{-1} yr^{-1} depending on fertilization rate, crop variety and year. The CO_2 fixed in the biomass of energy crops is reduced by up to 16% if direct N_2O emissions from soil and indirect N_2O emissions from NO_3 leaching and fertilizer production are included. Taking into account the main greenhouse gas emissions, which derive from the production and the use of N fertilizer, the growth of poplar and rye may replace the global warming potential of fossil fuels by up to 17.7 t CO_2 ha^{-1} yr^{-1} and 12.1 t CO_2 ha^{-1} yr^{-1}, respectively.

Contents

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1. Introduction

In order to fulfill the requirements of the Kyoto Protocol and face climate change, the production of biomass has been intensified worldwide and has a great potential, which is far away to be fully used yet [1,2]. Energy crop cultivation makes it possible to remove CO_2, and thermal conversion of these crops can act as a substitute for fossil fuels. A positive effect on CO_2 mitigation can be expected, however, this might be reduced by other greenhouse gases, which are released during the production and consumption of energy crops [3–6]. Emissions may occur either directly during agricultural operations such as fertilizing, ploughing and harvesting, or indirectly as a consequence of nitrate leaching, or during production and transport of fertilizers and pesticides. This study is not designed to employ a full life cycle assessment (LCA), which reflects a complete evaluation of all greenhouse gas sources and socio-economic aspects as emphasized by Hanegraaf et al. [7]. The focus of this study is on the use of mineral nitrogen fertilizer and its effect on the CO_2 balance of the production of one annual energy crop (rye) and one perennial energy crop (poplar) on a loamy sandy soil in Northeast Germany.

According to Wegener et al. [8], about 113 million tons of CO_2 equivalents are emitted from the German agricultural sector (Fig. 1). This amount does not include emissions linked with the production of mineral fertilizers. One-third (31.5%) of the agricultural sector derives from agricultural soils in the form of nitrous oxide (N_2O), a greenhouse gas, which is very important due to its global warming potential, 298 times higher than that of CO_2. Thus the CO_2 fixing capacity of renewable energy crops may be constrained. Agronomic practices such as tillage, harvesting and fertilizer applications can significantly affect the production and consumption of N_2O due to alteration of soil physical and chemical characteristics, and biochemical activities. Soil cultivation and precipitation affect the soil air exchange rate and thus influence microbial aerobic and anaerobic processes such as nitrification and denitrification [9–11]. Both processes may be stimulated after the application of nitrogen fertilizer, as reported by Freney [12].

Even the production of mineral nitrogen fertilizers results in considerable N_2O emissions besides the emission of CO_2 during this energy-consuming process [13,14]. In Western Europe 1.8% of total CO_2 and N_2O emissions and 0.9% of total energy consumption derive from the fertilizer industry [15]. Consequently, the emission of greenhouse gases through this pre-chain of biomass production comprises an important component of agricultural LCA [16]. It has been reported that the production of short rotation coppices such as poplar in particular needs only a low supply of nitrogen fertilizer [17,18]. Thus it may be hypothesized that poplar has a greater potential for reducing CO_2 emissions than the annual crop rye. The overall goal is to obtain more verified information about the ecological drawbacks of nitrogen fertilization and to find out at what fertilizer rate the highest net CO_2 sequestration can be expected from the production of rye and poplar.

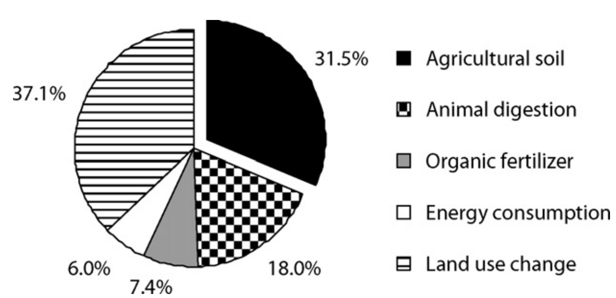

Fig. 1. Sources of greenhouse gases expressed as CO_2 equivalents from agriculture in Germany according to Wegener et al. [8]. Greenhouse gas emissions from agricultural soils were the main subject of this study.

2. Methods

2.1. System boundary

This study focused on the growing period of energy crops and the utilization of nitrogen fertilizer in the field. From this on-farm stage, the main components included in the CO_2 balance are both, the carbon fixation by above-ground crop biomass and direct and indirect greenhouse gas emissions from the soil. Carbon sequestration by below-ground biomass and by soil was not included in this study.

Among the pre-farm stages, only the production of mineral N fertilizer is taken into consideration, since it is known as a highly energy-consuming process [19,20]. In Germany, 1.8 million tons of mineral fertilizer nitrogen was sold in 2007/2008. This amount includes 0.81 million tons of calcium ammonium nitrate (CAN) nitrogen [21]. Since CAN played the main role among all nitrogen fertilizers applied in German agriculture and also in other European countries during the last ten years, this type of mineral nitrogen fertilizer has been evaluated in terms of CO_2 equivalents related to its manufacturing process [22].

Greenhouse gas emissions arising during the transport of raw materials and their products have been reported as playing a minor role of between 1% and 3% of total emissions during biomass production [23], and have therefore been neglected. Biomass yields were obtained after harvesting; however harvesting and post-harvest processes themselves have not been considered in this CO_2 balance.

2.2. Study area

The study was performed from February 1999 to December 2007 on an experimental field at the Leibniz-Institute for Agricultural Engineering (ATB) in Potsdam, Germany (52°26′N, 13°00′E). The topsoil (0–30 cm) can be characterized as loamy sand with a carbon content of up to 0.8% and pH 6.0 (Table 1). Deeper layers are relatively rich in organic matter, which must be due to former applications of lake sediments and other organic enrichments during a period of fruit-growing in the 1980s and before. The mean air temperature and precipitation during the study period were 10.1 °C and 580 mm yr^{-1}.

2.3. Field design

The experimental field with a total area of 4.1 ha was parcelled out for the cultivation trials in 1994 [24]. In our study, a CO_2 balance was drawn up for one perennial and one annual crop. The perennial crop was poplar (*Populus maximowiczii* × *P. nigra*), a short rotation crop with a four-year rotation period (study period 1999–2007), and the annual crop was rye (*Secale cereale* L.). Only the six years (1999, 2001, 2003, 2005, 2006 and 2007) when rye was planted at the same site were considered in case of rye. Both crops were arranged in

Table 1
Soil characteristics with grain sizes from Scholz [46] and C_{tot} and N_{tot} analyses from December 2005.

Soil horizon	Depth (cm)	Grain size (%)			C_{Tot} (g kg^{-1})	N_{Tot} (g kg^{-1})
		Sand	Silt	Clay		
Ap	0–30	77.9	15.9	6.2	7.6	1.04
Ah	30–60	75.7	18.3	6.0	5.8	0.75
Bt	60–82	62.0	20.6	17.4	5.8	0.49
Cv	>82	62.1	25.7	12.2		

rectangles each with an area of 104 m × 24 m, which were subdivided into four plots. Three times between April and May, nitrogen fertilizer (CAN) was applied to the plots with a total input of 75 N kg ha^{-1} yr^{-1} and 150 N kg ha^{-1} yr^{-1}. Further phosphorus and potassium fertilizers were applied every second year in the form of Kamex-superphosphate in the case of the 150 kg N plot and in the form of wood ash on the 75 kg N plot. An additional plot with no fertilizer applications was arranged as a control. No pesticides were applied throughout the study.

2.4. Direct N_2O emissions

Direct N_2O emissions from the soil were measured using closed cylindrical chambers placed on a collar with a volume of 0.064 m^3 (upper diameter 0.39 m, lower diameter 0.51 m, height 0.40 m). Measurements were performed four times a week in the morning during the whole years. The chambers were located within the stand of poplar (row distance 2.25 m) and rye (row distance 0.15 m). Gases were sampled in 125 ml evacuated glass vials at the beginning and the end of incubation after 60 min. During the incubation period the increase of N_2O emissions had been proved for linearity. Gas samples were analyzed using a gas chromatograph according to Loftfield et al. [25] at the same day.

The fertilizer-induced N_2O emission rate was calculated for each rate of fertilization by taking the difference between the mean values of the fertilized and the non-fertilized plots on a yearly basis. Then the nitrogen conversion factor is given by the ratio of emitted soil N_2O–N to the fertilizer nitrogen applied. The N_2O conversion factor induced by N fertilizer was calculated using

$$\text{EF applied N}\,(\%) = 100 \times \frac{(\text{N}_2\text{O-N}_{\text{fert}} - \text{N}_2\text{O-N}_{\text{non-fert}})}{\text{N}_{\text{fert}}}.$$

In the next step, emission factors are expressed as CO_2 equivalents per unit mass of fertilizer nitrogen in line with international greenhouse gas accounting practice [22].

2.5. Indirect N_2O emissions

Two indirect emission paths of N_2O after application of N mineral fertilizer were involved in this study—the volatilization of NH_3 and NO_x and the leaching of NO_3^-. It is suggested that both emission paths subsequently yield N_2O emissions. For the first path, default values were applied according to IPCC [22]. The second path, the leaching of NO_3^- from soil, was determined during one complete year of the study period using the resin core technique [26]. Resin cores had an inner diameter of 55 mm and a length of 100 mm and were filled with a mixture of pre-washed Amberlite MB 20 and quartz sand. Resin cores with 8 replicates at each plot were installed on 28 October 2005. Mounting was undertaken laterally from the side of a soil pit 90 cm beneath the soil surface. One year later on 7 November 2006, the cores were collected and cut into 3 layers (0–20, 20–60, 60–100 mm). The total fresh weight of each fraction was determined and an aliquot of about 10 g was extracted with 100 mL of 1 M KCl. NO_3^- contents were determined photometrically with an automatic flow analyzer (RFA-300, Alpkem Corp., Clackamas, OR and Skalar, The Netherlands). The top resin layer had the highest N concentrations and the middle one the lowest N concentrations, verifying that the capacity of the resin was sufficient to prevent break-through and no nutrients were lost by leaching. Only the top two resin layers were taken for flux calculations as described by Lehmann et al. [27]. Fertilizer-related leached nitrate, which accumulated in the resin cores, was calculated as

$$\text{NO}_3\text{-N}_{\text{leach}} = (\text{NO}_3\text{-N}_{\text{leach/fert}} - \text{NO}_3\text{-N}_{\text{leach/non-fert}}).$$

According to the guidelines of IPCC [22], indirect N_2O emissions are obtained by applying a conversion factor of 0.75%. The emission factor for N_2O followed by NO_3^- leaching was calculated using the expression

$$\text{EF} = 0.75\% \times \frac{44}{28} \times \frac{\text{NO}_3\text{-N}_{\text{leach}}}{\text{N}_{\text{fert}}}.$$

Finally, CO_2 equivalents are obtained from multiplying the emission factor with the global warming potential of 298.

2.6. Harvesting of annual and perennial energy crops

Poplar was harvested during the study period in January 2002 and December 2005 by contrast with winter rye, which was harvested six times during the study period in the months July and August of 1999, 2001, 2003, 2005, 2006 and 2007. In the intervening periods, this site was cultivated with hemp (2000), rape (2002), and triticale (2004).

Five subplots were harvested from each plot. Within the poplar plots, harvesting was performed from 10 m^2 subplots with a tractor-mounted cutter chipper. In the case of rye, biomass subplots were mowed from an area of 4 m^2. Biomass was weighed using an electronic balance in the field. Oven-dry mass was obtained from an aliquot of chopped biomass after drying at 106 °C.

2.7. Statistical analyses

Data of the factorial experiment were subjected to a one-way analysis of variance. Student's *t*-test was used for comparisons of results. Where significant effects were found, means were compared using the least significant difference test (LSD) at $p < 0.05$. All statistical analyses were performed using SAS-JMP 8.0.

3. Results

3.1. Biomass yield

During the study period of nine years, the plots with poplar were harvested twice during winter months in 2001/2002 and 2005/2006. Biomass yields from the shoots of rye were derived from annual harvesting, which was followed by ploughing and sowing in contrast to poplar, which remained alive and grew again after harvesting.

At both harvests of poplar there was a decrease in biomass yield due to fertilization, which however could not be proved statistically (2001/2002: $p = 0.066$, 2005/2006: $p = 0.303$). The average was 10.18 t ha^{-1} yr^{-1} at the non-fertilized control plot and 9.08 t ha^{-1} yr^{-1} at the plot fertilized with 150 kg ha^{-1} yr^{-1} (Table 2).

In case of the annual rye crop, significant fertilization effects were obtained. The mean biomass yield of fertilized rye (75 kg N, 150 kg N) exceeded that of the non-fertilized site by 38% and 47%, respectively. Very low yields were obtained for rye in the dry years of 1999 and 2003, when precipitation was below 450 mm yr^{-1}. For the biomass of poplar and rye, carbon contents of 48% and 50% respectively were taken from Lamlom and Savidge [28] and from own measurements as a basis for further calculation of CO_2 equivalents.

3.2. Soil N_2O emissions

Seasonal variability of N_2O emissions has already been reported earlier for the experimental field under study [29–31]. In Fig. 2, only two years from the nine-year study period are presented as an example, showing the seasonal pattern with N_2O emission rates, which are generally higher during the warm season in contrast to the cold season. Even the non-fertilized plots show this pattern, reflecting the effect of temperature-dependent mineralization of

Table 2
Above-ground biomass yield of energy crops at the ATB experimental field. Poplar was harvested every four years in contrast to rye harvested annually. All yield data are expressed on a yearly basis in tons dry matter ha^{-1} yr^{-1}. Values in one line followed by the same letter are not significantly different at $p < 0.05$.

		0 kg N	75 kg N	150 kg N
Poplar	2001/2002	9.91 a	9.62 a	9.07 a
	2005/2006	10.45 a	9.31 a	9.09 a
	Mean	**10.18 a**	**9.46 ab**	**9.08 ab**
Rye	1999	4.41 a	5.46 a	5.69 a
	2001	5.99 a	9.34 b	9.26 b
	2003	3.26 a	5.98 ab	6.37 b
	2005	4.52 a	7.78 b	9.54 c
	2006	8.33 a	10.34 b	9.39 c
	2007	5.14 a	4.96 a	6.34 b
	Mean	**5.28 a**	**7.31 b**	**7.77 b**

organic nitrogen compounds in the soil. On most days, N_2O emission rates followed the intensity of N fertilization, particularly after the periods of fertilization.

One extraordinary case was observed in 2006, when there were long-lasting high emission rates up to 1160 μg N_2O m^{-2} h^{-1} in the poplar plot fertilized with 75 kg N ha^{-1} (Fig. 2). It is suggested that the nitrogen excess was promoted after harvest and fertilizer application in April 2006. Thus a considerable amount of nitrogen could have been released as N_2O.

During the nine-year study period, the mean N_2O emission rate in the non-fertilized plot of rye was 1.0 kg N_2O–N ha^{-1} yr^{-1} and thus twice as high as in non-fertilized poplar (Fig. 3). This background emission is relatively high by comparison with studies from Malhi and Lemke [32], who found values of up to 0.3 kg N_2O–N ha^{-1} yr^{-1}. Even lower values of 0.14 kg N_2O–N ha^{-1} yr^{-1} were reported by Groeningen van et al. [33]. Significant differences in N_2O emission rates were obtained between the control and the fertilization rate of 150 N ha^{-1} yr^{-1}.

Considering N_2O emissions on our experimental field during the study period, the fertilizer-induced conversion factors were

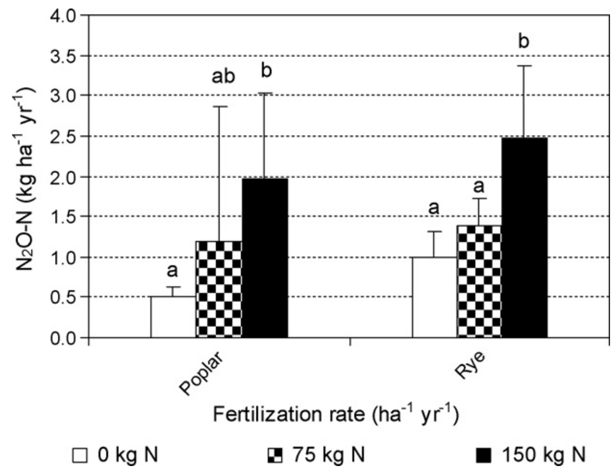

Fig. 3. Mean N_2O fluxes (+1SD) at the ATB experimental field between 1999 and 2007 (poplar $n = 9$, rye $n = 6$). Different letters between two bars reflect significant difference of $p < 0.05\%$.

0.75% for rye and 0.95% for poplar each as a mean of the 75 kg N and 150 kg N fertilization rate, if the N_2O emission rates of non-fertilized plots were taken into account. These factors are higher than those measured on the same experimental field earlier [29] and those measured at another site on sandy soils in the Netherlands [33].

3.3. NH_3 and NO_x volatilization

According to IPCC [22], it can be assumed that 10% of applied nitrogen mineral fertilizer is emitted by volatilization in the form of NH_3 and NO_x. IPCC [22] has set a default value of 1% of the volatilized fraction, which forms N_2O after deposition and transformation. This kind of emission is considered as indirect N_2O emission corresponding to 0.47 kg CO_2 per kg nitrogen in CAN (Table 3).

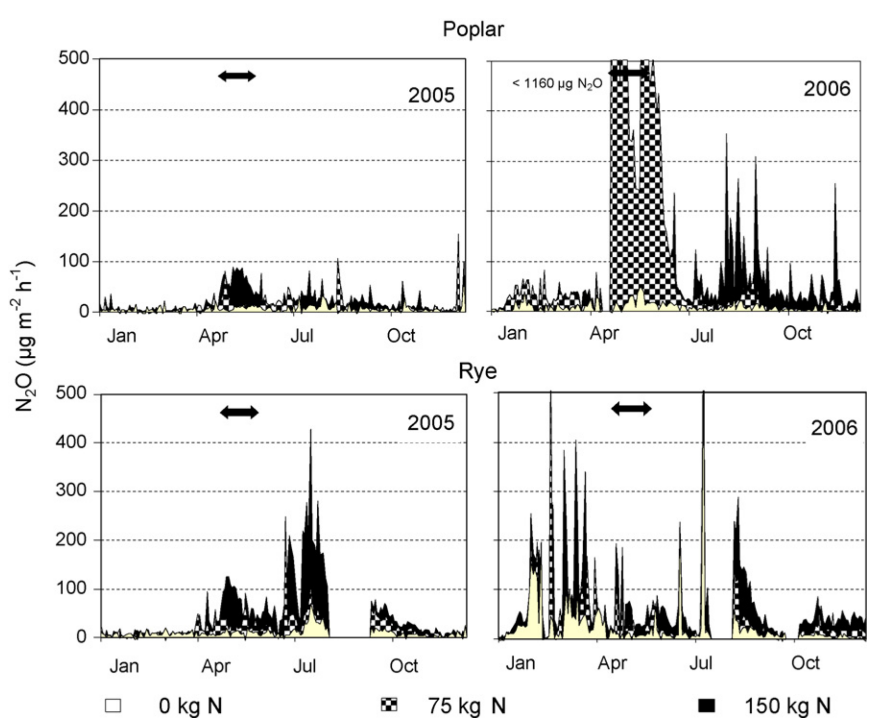

Fig. 2. Daily N_2O emission from perennial and annual crop plots at the ATB experimental field during a period of two years. Arrows indicate the period of CAN application.

Table 3
Greenhouse gas emissions from production and application of 1 kg nitrogen in CAN fertilizer. CO_2 equivalents derive from a global warming potential of 298:1 for N_2O:CO_2. Emission factors (EF) are expressed as unit mass per fertilizer product.

Source of greenhouse gas	CO_2 equivalents	Reference
Direct fertilizer-induced N_2O emission from soil		
EF = 0.75% for rye	3.51 kg CO_2	This study
EF = 0.95% for poplar	4.45 kg CO_2	This study
Indirect N_2O emission from leaching		
EF = 0.75% × 0.272 (leached fraction) = 0.204% for rye	0.96 kg CO_2	This study
EF = 0.75% × 0.157 (leached fraction) = 0.118% for poplar	0.55 kg CO_2	This study
Indirect N_2O emission from NH_3 and NO_x volatilization and redeposition EF = 1% × 0.1 (volatilized fraction) = 0.1%	0.47 kg CO_2	IPCC [22]
CO_2 emission from energy consumption required for NH_3 synthesis EF = 2.104 kg CO_2 (kg NH_3)$^{-1}$	2.61 kg CO_2	IPCC [22]
N_2O emission from HNO_3 manufacturing EF = 5.5 kg N_2O (Mg HNO_3)$^{-1}$	3.67 kg CO_2	UBA [34]
CO_2 emissions from $CaCO_3$ manufacturing and decaying after soil application	0.45 kg CO_2	IPCC [22]

3.4. Leaching

During a complete year from 2005 to 2006, up to 41 kg nitrogen was leached as nitrate (Fig. 4). Generally, the higher the fertilization rate, the higher the amount of leached nitrate. A survey on the experimental field had shown that the different fertilization rates were clearly reflected by the mean soil NO_3–N with 0.5 mg kg^{-1}, 0.9 mg kg^{-1} and 1.6 mg kg^{-1} for the non-fertilized plots and the plots fertilized with 75 kg N and 150 kg N, respectively [31]. Taking a soil density of 1.5 g cm^{-3} [5], that resulted in 2.3 kg N ha^{-1}, 4.0 kg N ha^{-1} and 7.2 kg N ha^{-1} within the 0–30 cm horizon.

The loss of fertilizer nitrogen adjusted by the loss from the non-fertilized plot was 8% and 24% for poplar and 37% and 17% for rye in terms of fertilizer rates of 75 and 150 kg N. These leaching ratios are in the range of 30% given for regions with a positive water balance by the IPCC [22]. Leached nitrogen compounds may result in indirect N_2O emissions and were calculated to be 0.118% and 0.204% of applied N for poplar and rye, respectively (Table 3). Transforming the indirect N_2O emissions to CO_2 equivalents resulted in values ranging between 0.26 kg CO_2 (kg N)$^{-1}$ and 0.84 kg CO_2 (kg N)$^{-1}$ for poplar and between 0.60 kg CO_2 (kg N)$^{-1}$ and 1.32 kg CO_2 (kg N)$^{-1}$ for rye, respectively. The mean value for each energy crop is given in Table 3.

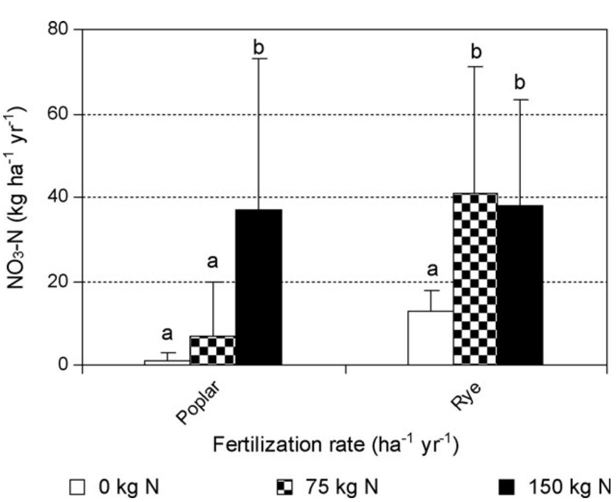

Fig. 4. Amount of NO_3–N (mean + 1SD), which was leached and fixed at a depth of 0.9 m at the ATB experimental field during a period of one year from 2005 to 2006 (n = 8). Different letters between two bars reflect significant difference of $p < 0.05$%.

3.5. CO_2 equivalents from the manufacturing of calcium ammonium nitrate (CAN)

CAN fertilizer is a mixture of NH_4NO_3 and $CaCO_3$ with a mass N:$CaCO_3$ ratio of about 1:1, containing up to 27% nitrogen and 10% calcium. Nitrogen occurs half in the nitrate form and half in the ammoniacal form. One kilogram of nitrogen from CAN fertilizer corresponds to 2.846 kg NH_4NO_3, which is produced from NH_3 and HNO_3. The majority of greenhouse gas emissions are made up of CO_2 emissions from ammonia synthesis and N_2O emissions from nitric acid production. Considering an emission factor of 2.104 kg CO_2 for the synthesis of 1 kg NH_3 [22] and the global warming potential of 298:1 for N_2O:CO_2, we obtain a CO_2 equivalent of 2.61 kg, which corresponds to the production of 1 kg CAN nitrogen (Table 3). Furthermore, when HNO_3 is manufactured by catalytic NH_3 oxidation, N_2O is released as a by-product. The amount of N_2O depends on the state of technology and is subject to a high variability between 2 kg N_2O (Mg HNO_3)$^{-1}$ and 9 kg N_2O (Mg HNO_3)$^{-1}$ [22]. Applying an emission factor of 5.5 kg N_2O (Mg HNO_3)$^{-1}$ [34], the production of required 2.241 kg HNO_3 yields CO_2 equivalents of 3.67 kg CO_2. In the case of $CaCO_3$ production only about 0.011 kg CO_2 (kg $CaCO_3$)$^{-1}$ is emitted [22]. This is far below the emission of 0.44 kg CO_2 (kg $CaCO_3$)$^{-1}$ which results from application to soil. The overall emissions released to produce 1 kg N as CAN fertilizer can be expressed as 6.29 kg CO_2 equivalents.

3.6. CO_2 balance of the production of energy crops

The total gain of CO_2 equivalents, which may be calculated from the carbon fixed in the biomass, ranged between 64.0 t CO_2 ha^{-1} and 71.6 t CO_2 ha^{-1} during a rotation of four years for poplar, that are 16.0 t CO_2 ha^{-1} yr^{-1} and 17.9 t CO_2 ha^{-1} yr^{-1} and between 9.7 t CO_2 ha^{-1} yr^{-1} and 14.2 t CO_2 ha^{-1} yr^{-1} for rye (Fig. 5). If greenhouse gas emissions from the soil and from the production of mineral fertilizer (CAN) are included, then CO_2 fixation is counteracted by the intensity of fertilization. The fertilization rate of 150 kg ha^{-1} yr^{-1} resulted in a reduction of 2.1 t CO_2 ha^{-1} yr^{-1} and 2.3 t CO_2 ha^{-1} yr^{-1} for poplar and rye, respectively.

Among direct and indirect greenhouse gas emissions, direct N_2O soil emissions contributed the major amount of CO_2 equivalents. The maximum rate of indirect N_2O emissions as a consecutive process of NO_3 leaching and NH_3 and NO_x volatilization was 0.20 t CO_2 ha^{-1} yr^{-1} in the case of poplar (150 kg N) and thus did not play an important role. Considering all calculated and estimated CO_2 equivalents released by the production of poplar and rye, the positive effect of CO_2 saving is reduced by 1.3% (poplar

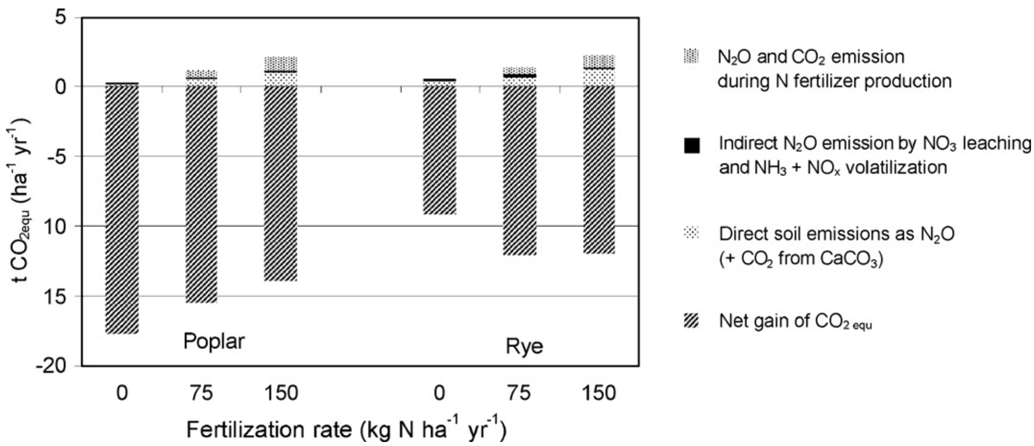

Fig. 5. CO_2 balance during the production of energy crops at the ATB experimental field between 1999 and 2007.

0 kg N) and 15.7% (rye 150 kg N). There is a net gain of CO_2 equivalents between 13.9 t CO_2 ha^{-1} yr^{-1} and 17.7 t CO_2 ha^{-1} yr^{-1} for poplar and between 9.2 t CO_2 ha^{-1} yr^{-1} and 12.1 t CO_2 ha^{-1} yr^{-1} for rye. From 1999 to 2007 the reduction of global warming equivalents (GWE) by greenhouse gas emissions was highest at the non-fertilized plot of poplar and at the fertilized plots of rye with no difference between the two fertilization rates (Fig. 5).

4. Discussion

4.1. Mineral N fertilizer

The production of N fertilizer contributes to a high share of fossil energy consumption in crop production, which has to be taken into account when criteria for sustainable agricultural production are defined. Furthermore, even at the pre-farm stage the production of N fertilizer leads to considerable N_2O emissions, which reduce the positive effect of energy crops. At the on-farm stage, N_2O emission occurs as a natural process, which is accelerated after application of N fertilizer. Mean values of N_2O emission in this study are still in the range of 1.0%, which is generally considered as a tolerable mean conversion factor for agricultural soils of temperate regions, used as default value for direct N_2O emissions in greenhouse gas inventories [22]. When considering the non-fertilized poplar plots, the conversion of 0.95% of fertilizer nitrogen to N_2O–N appears to be rather high for a perennial crop. It is mainly caused by the high N_2O emission rates in 2006, pointing to the strong impact of hot spot events on the nitrogen conversion factor [4]. Even higher fertilizer-induced N_2O conversion factors of up to 5% were reported by Rudaz et al. [10] on a permanent pasture with a sandy loam, and by Flechard et al. [35] on grassland soils in Europe. Also high N_2O conversion factors were obtained from Australian sugarcane soils [36]. The values varied between 1.2 and 6.7%, indicating higher and more variable N_2O emissions as given in the IPCC guidelines. Up-scaling of N fluxes remains highly uncertain as long as no better data exist for regional-specific conditions and for agricultural practices. Therefore, N flux verification procedures are needed to assess compliance with international protocols [37].

If CO_2 equivalents from direct and indirect greenhouse gas emissions as a consequence of fertilization are added, then up to 16% of the CO_2 fixed in the biomass is counterbalanced in this study. This is in accordance with data from Lewandowski and Schmidt [38], who found that 5–20% of the amount of energy contained in the harvested biomass is necessary as input to obtain the biomass being produced for solid fuel. Therefore those crops that need little or no N fertilization do well for the environment.

4.2. Energy and C balance

Energy input is needed for biomass production and the net energy yield provides a picture of the efficiency of the energy crop in replacing fossil energy and the avoidance of greenhouse gas emissions.

Cumulative energy demand for the production of solid biofuels can be distinguished between cereals and poplar with about 20 GJ ha^{-1} yr^{-1} and 3–7 GJ ha^{-1} yr^{-1}, respectively [39]. The major role in producing and harvesting energy crops is played by the energy input needed for cultivation as shown for poplar by Gasol et al. [40]. This includes the use of fertilizer, which was less effective in poplar compared with rye in our study. If poplar is produced and N fertilizer can be saved, the final cost must be lower for poplar than for energy rye. Besides the energy use in fertilizer production and field N_2O emissions, the carbon content of the soil may also play a key role in the net global warming potential. Mosier et al. [41] reported that soil organic carbon storage decides whether a system is a sink or a source of CO_2. The carbon tradeoff on the experimental field at Potsdam has been studied recently by Strähle [42], who calculated that the soil organic carbon stocks in the top 30 cm of perennial crops were significantly increased compared with annual crops. More long-term studies are needed to verify these first results, which are based on soil conditions with an unusually rich A-horizon. This could have influenced the tree growth and also the organic carbon storage in the soil.

The CO_2 balance presented here derives from only a few selected elements of a LCA, which are believed to play important roles. Post-harvest processes as well as additional greenhouse gas emitted during the combustion of biomass are reportedly also relevant [6], but were outside our system boundary.

4.3. Assessment of energy crops

As far as possible, each nitrogen pathway was validated by experimental data, which should reduce the uncertainty in assessing the production of specific energy crops. On the basis of the CO_2 balance deriving from our nine-year study, perennial crops obviously have some advantages over annual crops as already reported by Kaltschmitt et al. [43], Hanegraaf et al. [7] and Rowe et al. [44]. An overall environmental assessment of biomass production has to include other features besides the input of fertilizers, such as for example the input of pesticides. In our study however, we waived the use of pesticides, which are commonly used primarily for annual crops. Another economic advantage of perennial crops is a harvest cycle of four or more years, which allows a low frequency of required machine operations. This

generally results in ecological benefits of reduced N_2O emissions due to lower soil disturbance.

The real environmental and economic benefit of energy crops depends on region-specific conditions as well as on the system boundary chosen for the assessment. A complete LCA as recently demonstrated by Biswas et al. [14] for wheat production in Australia has clearly distinguished between greenhouse gas emissions from pre-farm, on-farm and post-farm stages. In that case, pre-farm processes such as the production of mineral fertilizer and herbicides played the major role in greenhouse gas emissions. It could also be shown that in situ measurements of N_2O emissions from the soil have a considerable effect on the final result of a LCA, although the N_2O soil emission factor, determined in the Australian study, was only one sixth of the IPCC default value of 1%. This underlines once more the great value of data from in situ measurements, which should be consulted for the careful assessment of energy crops as far as available. Crutzen et al. [6] concluded from the evaluation of global N_2O budgets, taking into account global N fixing (biologically, by industrial fixation and by fossil fuel burning), that the overall N conversion factor should be in the range between 3% and 5%. Based on this, they derived a criterion for the ratio of N to dry matter in the plant material, which indicates to what degree the reduced global warming achieved by using biofuels instead of fossil fuel as energy sources is counteracted by release of N_2O. This discrepancy between a "global N_2O emission factor" related to "global N fixing" and the IPCC default value for N fertilization results from the different ways of consideration. IPCC factors are given for detailed processes, e.g. fertilization or volatilization. Livestock production cycles N via the path:

$$\text{forage} \rightarrow \text{feeding animals} \rightarrow \text{manure storage}$$
$$\rightarrow \text{manure application as fertilizer} \rightarrow \text{plants} \rightarrow \text{forage}.$$

N_2O is emitted directly due to fertilization, but also indirectly via volatilization and leaching in the course of each cycle. When the total N_2O emissions of the whole cycle of livestock breeding are related to the total input of fixed N (mainly mineral fertilizer), then emission factors will result that are several times higher compared with the N_2O emission factor of annually applied N fertilization. The best way of producing energy crops with a high nitrogen and energy use efficiency is to choose a crop, which efficiently transforms the growth factors into harvestable energy. As outlined by Lewandowski and Schmidt [38], this is realized by the production of perennial C_4 grasses such as *Miscanthus* $\times$ *giganteus*. giganteus. On cooler sites, the production of short rotation coppices is suggested in order to use nutrient and energy resources most efficiently. The use of former arable soils particularly is recommended, since most agricultural soils are enriched with macronutrients such as nitrogen [45]. After all, the experimental field under study had been a fruit-growing plantation with input of organic residues before the experimental field was established. This should have enabled a good and in part excessive nutrient supply in the soil. Additional hot spots of N_2O emission, which could not be explained in detail, could have been the reason for the relatively high conversion of mineral N to N_2O.

It could be shown that on the loamy sand under study, poplar had a greater potential for reducing CO_2 emissions than rye. In contrast to rye with its highest mitigation of CO_2 equivalents at the fertilization rates of 75 kg N ha^{-1} yr^{-1} and 150 kg N ha^{-1} yr^{-1}, an inverse pattern occurred for poplar. Thus the saving of nitrogen fertilizer for biomass production characterizes poplar as a valuable energy crop.

5. Conclusions

The production of energy crops facilitates the removal of CO_2 and thermal conversion of these crops is one way of substituting them for fossil fuels. However, a distinction must be made between different crops. How far their production can be considered as economical and environmentally acceptable depends on the intensity of negative drawbacks, such as the emission of N_2O. One of the most important factors controlling N_2O emissions is the application of nitrogen fertilizer. In this study, there was a loss of CO_2 equivalents fixed in the biomass of up to 16%. Production and application of N fertilizer is the main reason for direct and indirect greenhouse gas emissions. Consequently, reducing the input of N fertilizers to the fields would be one way of mitigating N_2O emissions and thus enhancing the CO_2 mitigation potential of energy crops. Therefore further research should focus on energy crops and new genotypes, which have both a high biomass yield and a low nitrogen requirement.

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